Latest Experimental Information on ϵ'/ϵ

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Abstract. We review the latest experimental results in searching for "direct" CP-violation by measuring the CP-violating parameters $Re(\epsilon'/\epsilon)$ in neutral kaon decays. The Recent result from Fermilab-KTeV $Re(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$, and the new preliminary result from CERN-NA48 $Re(\epsilon'/\epsilon) = (14.0 \pm 4.3) \times 10^{-4}$, are presented. Both experiments, though using very different techniques, have now performed very well by collecting millions of events for all four relevant decay modes of $K_{L,S}$ to $\pi^+\pi^-$ and $\pi^0\pi^0$ simultaneously. The current world average on this important measurement is $Re(\epsilon'/\epsilon) = (19.3 \pm 2.4) \times 10^{-4}$ with a $\chi^2/ndf = 11.1/5$, establishing the existence of "direct" CP-violation. The experimental status of such crucial measurements and the future prospects are also discussed here.

INTRODUCTION

Studying symmetry or the lack of symmetry in nature is a powerful tool in modern physics to understand many of its underlying fundamental laws of nature. The big bang is thought to have created equal amounts of matter and antimatter, but to the best of our knowledge, all the antimatter has disappered along with most of the matter. The reason is not known yet, but the clue lies in understanding the symmetry, or the lack of it, between the basic interaction of matter and antimatter. Three of the most important symmetry operations in physics are: charge conjugation, C, in which particles are replaced by their anti-particles; parity inversion, P, in which all three spatial coordinates are reversed; and time reveral, T. We believe that the "violation" of two of these symmetry operations – charge conjugation and parity inversion, combined as CP – is intimately involved in the dominance of matter over anti-matter in the universe.

CP violation was first discovered in 1964 by Cronin and Fitch [1]. They observed that if you waited long enough so that only the long-lived kaon were present in a K^0 beam, you will occasionally see two-pion decays at a rate of 1000 times smaller than the short-lived kaon decay rate. This could be explained by the mixing phenomena where a small amount (0.23%) wrong CP states was present in both the long-lived kaon, K_L and the short-lived kaon, K_S. For more than 35 years, the CP violation has only been observed in weak decays and so far only in the neutral kaon

TABLE 1. Experimental measurments on $\mathrm{Re}(\epsilon'/\epsilon)$ since 1986.

Experiments	Year Published	$\mathrm{Re}(\epsilon'/\epsilon)$ $(\times 10^{-4})$
E731A [7]	1988	(32 ± 30)
NA31 ('86) [8]	1988	(33 ± 11)
E731B (20%) [9]	1990	(-4 ± 15)
E731B (final) [10]	1993	(7.4 ± 5.9)
NA31 (final) [11]	1993	(23.0 ± 6.5)
KTeV (23% '96-'97) [12]	1999	(28.0 ± 4.1)
NA48 ('97) [13]	1999	(18.5 ± 7.3)
NA48 ('98 prelim.) [14]	2000	(12.2 ± 4.9)
Average		(19.3 ± 2.4)
		$(\chi^2/ndf = 11.1/5)$

system, e.g. charge asymmetry δ_l in K_{e3} and $K_{\mu3}$; η_{+-}, η_{00} and $\eta_{+-\gamma}$ in $K_L \to 2\pi$ and $K_L \to \pi^+\pi^-\gamma$ decays [2]; as well as the recent CP-odd and T-odd angular asymmetry in $K_L \to \pi^+\pi^- e^+ e^-$ [3].

While CP violation can be accommodated within the Standard Model with three generations of quark families [4], we still do not fully understand the *origin* of this violation and do not know whether the Standard Model provides the *sole* source of CP violation or not [5]. The search for a more complete understanding of CP violation has been the driving force behind a variety of recent kaon experiments, such as KTeV, NA48 and KLOE, as well as B-factory experiments. Besides a small amount of unequal mixture can give such tiny effect, called indirect CP-violation parametrized by ϵ; there are also other decay processes [6] in the Standard Model which can give a new kind of CP-violation directly, smaller than ϵ, which has only been established very recently [11] [12]. This effect referred to as "direct" CP-violation and parametrized by ϵ' which contribute differently to the decay rates of $K_L \to \pi^+\pi^-$ versus $K_L \to \pi^0\pi^0$ (relative to the corresponding K_S decays), and would be observed as a nonzero value in the ratio of $\mathrm{Re}(\epsilon'/\epsilon)$.

Experimentally we measure the double ratio R of the four 2π decay rates,

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \approx 1 - 6\mathrm{Re}(\epsilon'/\epsilon). \qquad (1)$$

Table 1 lists the $\mathrm{Re}(\epsilon'/\epsilon)$ measurements since 1986 including the most recent results.

The standard Cabbibo-Kobayashi-Maskawa (CKM) model accomodates CP violation with a complex phase in the quark mixing matrix. However, the theoretical calculations of $\mathrm{Re}(\epsilon'/\epsilon)$ are still uncertain depending on several input parameters and on the method used to estimate the hadronic matrix elements [15], though the recent estimates had favored non-zero values somewhat below 10^{-3}. Alternatively, a "superweak" interaction [16] could also produce the observed CP-violating mixing effect (ϵ) but would give $\mathrm{Re}(\epsilon'/\epsilon) = 0$. Therefore, a non-zero measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ would rule out the possibility that a superweak interaction is the sole source of CP violation, and would establish the "direct" CP-violation phenomenon
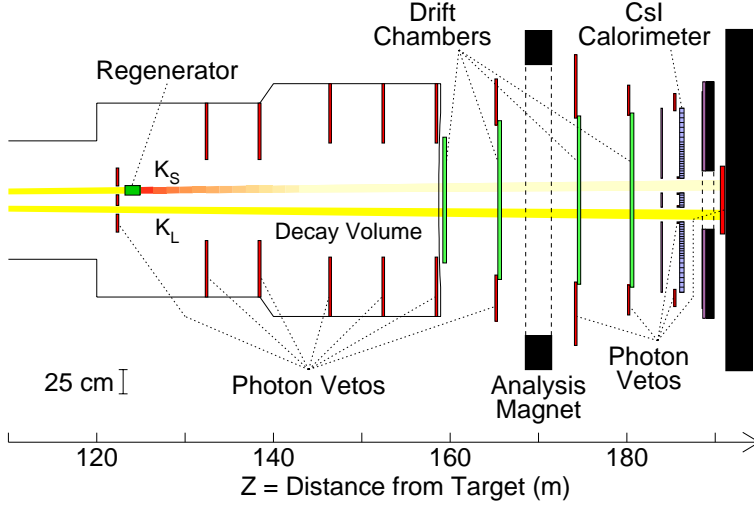
FIGURE 1. Plan view of the KTeV apparatus with double kaon beam as configured to measure $\mathrm{Re}(\epsilon'/\epsilon)$. The evacuated decay volume ends with a thin vacuum window at $Z = 159\ m$ followed by charged spectrometer and CsI calorimeter.

from the decay process itself.

If the direct CP violation exists, not only we would observe a non-zero value for $\mathrm{Re}(\epsilon'/\epsilon)$, but also we would observe very rare direct CP-violating kaon decay modes, such as $K_L \rightarrow \pi^0 e^+ e^-$, $K_L \rightarrow \pi^0 \mu^+ \mu^-$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$. The probability of observing such rare decays is quite small, less than 10^{-10} or 10^{-11}. Current experiments are barely reaching this sensitivity [17] and the search is still on-going.

Experimental Challenges and Methods

To measure the double ratio R we need both K_L and K_S decays with high statistics. A high precision electromagnetic (EM) calorimeter is required to measure the $\pi^0 \pi^0$ mode which decays to 4γ's, and match the resolution of a charged spectrometer for the $\pi^+ \pi^-$ mode. Since the γ's and charged pions can not be measured with the same detector element, experiments are looking for techniques would cancel the systematics, such as the double kaon beam technique used in E731, KTeV and NA48, the moving K_S target station used in NA31, as well as the K_S lifetime weighting method used in NA48. Various systematic sources have to be controlled and understood well in such high-rate experiments, such as backgrounds, detector or reconstruction inefficiencies, accidental losses and acceptance corrections, as well as the energy scales and non-linearity of the detector response.

The KTeV experiment (shown in Fig. 1) was designed to improve on the previous experiments and ultimately to have the sensitivity to establish "direct" CP-violation if $\mathrm{Re}(\epsilon'/\epsilon)$ is on the order of 10^{-3} with a sensitivity of 10^{-4}. The experimental technique was essentially the same as in E731 [18] with many improvements
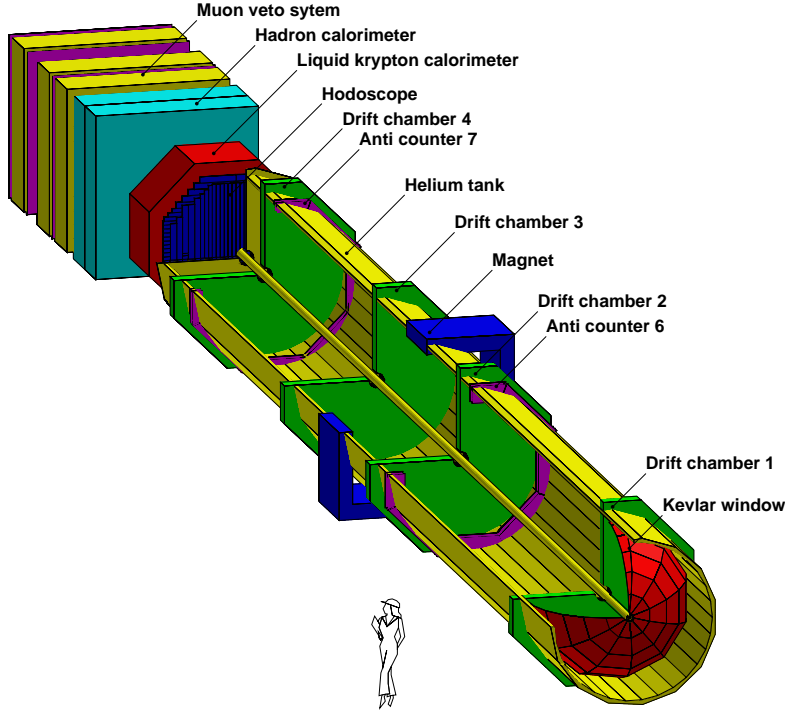
FIGURE 2. NA48 detector layout after the vacuum decay region.

in beam and detector performance. Double kaon beams from a BeO target (produced from an 800 GeV/c proton beam striking at 4.8 $mrad$ angle with an intensity of 4.5×10^{12} per pulse) was used to enable the simultaneous collection of K_L and K_S decays to minimize the systematics due to time variation of beam flux and detector inefficiencies. A precision magnetic spectrometer (with 412 MeV/c p_T kick in KTeV but 200 MeV/c for E731) was used to minimize backgrounds in the $\pi^+\pi^-$ samples and to allow *in situ* calibration of the calorimeter with electrons. A high precision EM calorimeter, 3100-crystal Cesium Iodide (CsI) array, was used in KTeV instead of the lead-glass calorimeter in E731 for $\pi^0\pi^0$ reconstruction and better background suppression. Superb mass resolutions (1.5 MeV/c^2 for $\pi^0\pi^0$ and 1.6 MeV/c^2 for $\pi^+\pi^-$) and photon energy resolution (better than 0.7% above 20 GeV/c^2) were achieved. Nearly hermetic photon vetoes were employed for further background reduction for the $\pi^0\pi^0$ mode. A new beamline was constructed for KTeV with cleaner beam collimation and improved muon sweeping. While the method of producing a K_S beam (by passing a K_L beam through a "regenerator") was also the same as E731, the KTeV regenerator was made of scintillator and was fully active to reduce the scattered background to the coherently regenerated K_S. Unlike E731, both $\pi^+\pi^-$ and $\pi^0\pi^0$ data were taken simultaneously in KTeV.

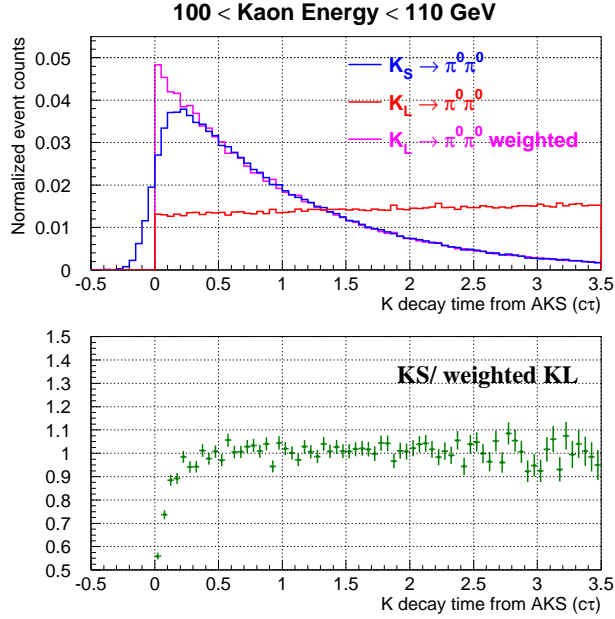On the other hand, NA31/NA48 started with quite orthogonal techniques. First,

FIGURE 3. NA48 weighting method as shown for $2\pi^0$ decay time distribtion and the ratio.

NA31 collected data alternately between K_L and K_S mini-run periods with separate targets for a single K_L or K_S beam and with different proton beam energy and intensity. In the K_S runs, there was a K_S target train moving along the 50 m decay region to provide 41 K_S target stations mimicking the K_L decay distribution to minimize the acceptance differences and corrections. A non-magnetic spectrometer was used to collect $\pi^+\pi^-$s and a liquid argon calorimeter was used for detecting $2\pi^0$s. The results of NA31 (shown in Table 1) gave a first indication of a possible 3σ non-zero $\mathrm{Re}(\epsilon'/\epsilon)$. The result of E731, consistent with zero, did not confirm this finding.

The NA48 experiment (shown in Fig. 2) was designed to measure $\mathrm{Re}(\epsilon'/\epsilon)$ with an accuracy of 2×10^{-4}. The principle of NA48 is to use nearly collinear K_L and K_S beams pointing at the center of the detector with similar momentum spectra and to detect all 4 decay modes at the same time. By applying a K_S lifetime weighting procedure to the events of K_L decays in both modes, the difference of acceptance between K_L and K_S can be largely reduced (as shown in Fig. 3).

The K_L beam was produced from a 450 GeV/c proton beam (with intensity 1.5×10^{12} per pulse) striking a Be target at 2.4 $mrad$. A small amount of protons behind the target were channeled and deflected back along the K_L beam after being identified by a tagging hodoscope. The proton beam of intensity 3×10^7 per pulse struck a second target located 120 m downstream and 72 mm above the K_L beam to produce the K_S beam. The beginning of the decay volume was defined for K_S by an anti-counter as a hardware veto to remove K_S decays upstream. The

decay region extended over 90 m inside a vacuum tank terminated by a thin kevlar window. Downstream of the vacuum decay region, the magnetic spectrometer (with 265 MeV/c p_t kick) was used for $\pi^+\pi^-$ with a mass resolution of 2.5 MeV/c^2. A quasi-homogeneous liquid krypton (LKr) calorimeter with 13212 projective towers was used for the precision measurement of the neutral mode. The reconstructed π^0 mass resolution for $2\pi^0$ decays was about 1 MeV/c^2. Only events within 3.5 τ_S lifetimes would be accepted for the analysis as shown in Fig. 3. A high speed, high bandwidth data acquisition system and pipeline readout systems were built for collecting a large quantity of good data (e.g. 50 Tbytes per year).

KTEV RESULTS AND STATUS

KTeV took high statistics 2π data in two periods, 1996-1997 and 1999 fixed target runs at Fermilab. The 1996-1997 data sample gives about 4 million $K_L \to \pi^0\pi^0$ (the limiting statistics mode) and for the 1999 run about 4.5 million $K_L \to \pi^0\pi^0$ decays.

First result of Re(ϵ'/ϵ) based on a sub-sample from 23% of 1996-1997 data sample of KTeV was published in 1999 [12]. The Re(ϵ'/ϵ) was extracted from the background-subtracted data using a fitting program which analytically calculates regeneration and decay distributions accounting for $K_S - K_L$ interference. The net yields after background subtraction are 2.607M $\pi^+\pi^-$ events in the vacuum beam, 4.516M $\pi^+\pi^-$ in the regenerator beam, 862K $\pi^0\pi^0$ in the vacuum beam and 1.434M $\pi^0\pi^0$ in the regenerator beam. After the monte carlo acceptance correction, the resulting prediction for each decay mode is integrated over Z and compared to data in 10 GeV bins of kaon energy. CPT symmetry is assumed, and the values of $K_S - K_L$ mass difference (Δm) and K_S lifetime (τ_S) are fixed to PDG values [2]. The regeneration amplitude is allowed to float in the fit, but constrained to have a power law dependence on kaon energy, with the phase determined by analyticity [18] [19]. The kaon energy distributions are also allowed to float for $\pi^+\pi^-$ and $\pi^0\pi^0$ modes in each energy bin (24 fit parameters in all).

Fitting was done "blind", by hiding the value of Re(ϵ'/ϵ) with an unknown offset between η_{+-} and η_{00}, until after the analysis and systematic error evaluation were finalized. The final fit result is Re(ϵ'/ϵ) = $(28.0 \pm 3.0) \times 10^{-4}$, where the error is statistical only with a χ^2 of 30 for 21 degrees of freedom. Table 2 summarize the studies of various systematics where the details can be found in reference [12]. The total systematic error is 2.8×10^{-4}. Effects due to accidental activities were taken into account in the monte-carlo acceptance simulation by overlaying the random accidental triggers taken during the run, on top of monte-carlo events. Figure 4 shows the data vs monte-carlo comparisons for the systematic studies of acceptance. Several cross-checks on this Re(ϵ'/ϵ) result have been performed in this analysis. Consistent values were obtained at all kaon energies (see Fig. 5), and there was no significant variation as a function of time or beam intensity.

KTeV has measured Re(ϵ'/ϵ) = $(28.0 \pm 3.0\ (stat) \pm 2.8\ (syst)) \times 10^{-4}$; combining

TABLE 2. Systematic uncertainties for KTeV Re(ϵ'/ϵ).

Source of Uncertainty	Uncertainty ($\times 10^{-4}$) $\pi^+\pi^-$	$\pi^0\pi^0$
Trigger and Level 3 filter	0.5	0.3
Energy scale, nonlinearity	0.1	0.9
Detector calibration, alignment	0.3	0.4
Analysis cut variations	0.6	0.8
Background subtraction	0.2	0.8
Detector aperture, resolution	0.5	0.5
Drift chamber simulation	0.6	-
Z dependence of acceptance	1.6	0.7
Monte Carlo statistics	0.5	0.9
Kaon flux and physics parameters	0.35	
TOTAL	2.8	
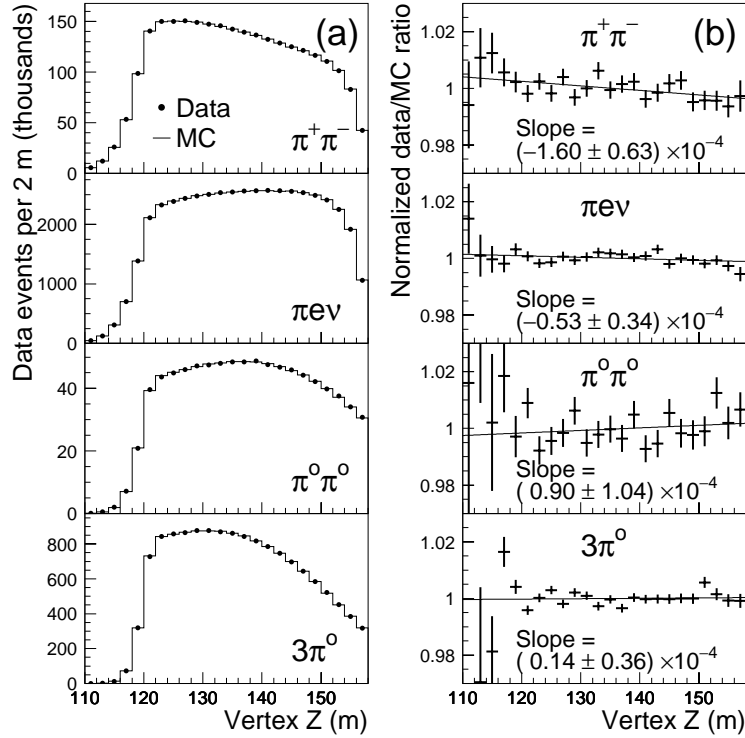
FIGURE 4. (a) Data versus Monte Carlo comparisons of vacuum-beam decay vertex Z distributions for $\pi^+\pi^-$, $\pi e\nu$, $\pi^0\pi^0$, and $3\pi^0$ decays in KTeV. (b) Linear fits to the data/MC ratio of Z distributions for each of the four decay modes.
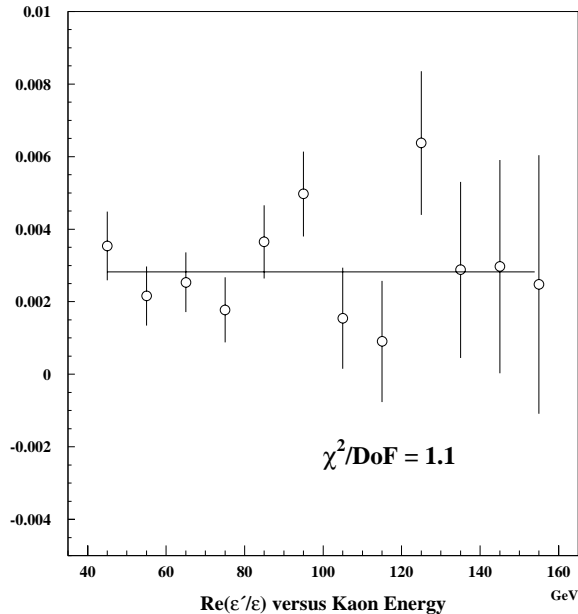
FIGURE 5. A systematic check of $\mathrm{Re}(\epsilon'/\epsilon)$ vs kaon energy for KTeV.

errors in quadrature, $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$. This result, nearly 7σ above zero, firmly establishes the existence of CP-violation in a "decay process", agreeing better with the earlier measurement from NA31 than with E731 and shows that a superweak interaction cannot be the sole source of CP-violation in the K meson system.

The rest of data from 1997 KTeV run are currently being analyzed to reduce both statistical and systematic uncertainties. More data have been taken in 1999 run with the aim of doubling the statistics with much improved detector performance and additional systematic checks, such as drift chamber efficiency in the beam region, reliable CsI readout electronics and better calibration, intensity studies and regeneration studies. We expect KTeV will reduce the $\mathrm{Re}(\epsilon'/\epsilon)$ statistical uncertainty to $\sim 1 \times 10^{-4}$ and lower the systematics to a similar level.

NA48 RESULTS AND STATUS

NA48 at CERN also started data taking in 1997. Since then they have acquired good statistics in three running periods. The data sample for 1997 run gave 0.49 million $K_L \to \pi^0 \pi^0$ decays and for 1998 run 1.14 million, for 1999 run about 2 million $K_L \to \pi^0 \pi^0$. The first result of $\mathrm{Re}(\epsilon'/\epsilon)$ based on the smaller 1997 data sample from NA48 was published in 1999 [13]. A new preliminary result with the larger 1998 data sample has been anounced recently [14]. The detector performance has been improved over the years, such as fixing the dead strips and the blocking
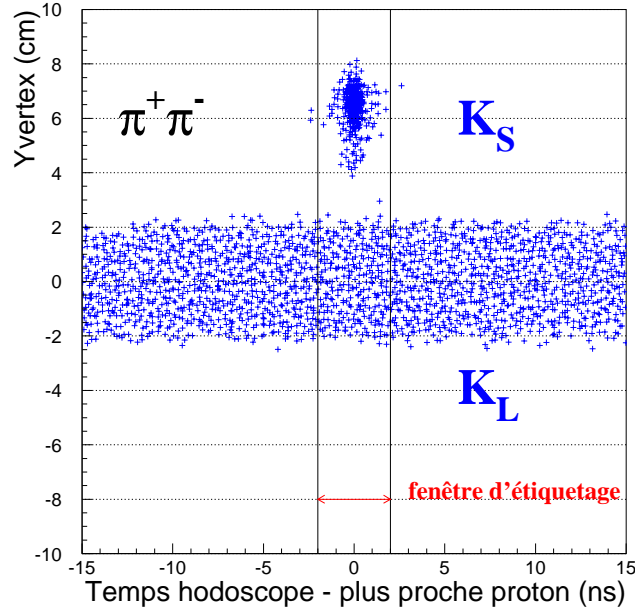
FIGURE 6. Distribution of minimum tagging time-of-flight versus decay y-vertex for the $\pi^+\pi^-$ data sample from NA48 experiment.

capacitors in LKr calorimeter, level-2 charged trigger efficiencies as well as stable detector running and data collection.

The K_L and K_S decays were separated by the tagging system by requiring events to fall into a $\pm 2ns$ time-of-flight window between the event time in the detector and the time in the tagger as K_S. Events outside this window were treated as K_Ls. This can be measured quite well with the charged mode data sample as shown in Fig. 6. The mistagging probability for a K_L to be counted as K_S due to accidentals in the tagging counter was measured to be $\alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$ and the tagging inefficiency for K_S was $\alpha_{SL}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$. Tagging differences between $\pi^0\pi^0$ and $\pi^+\pi^-$ mode would bias the $\text{Re}(\epsilon'/\epsilon)$ measurement. For the neutral mode, events with π^0 Dalitz decays or photon conversion as well as a special K_S only run limited the difference between α_{SL}^{00} and α_{SL}^{+-} to be less than 0.5×10^{-4}. The mistagging probability for the $\pi^0\pi^0$ mode can only be checked by comparing the side bands in the untagged K_L time window, between $\pi^0\pi^0$ and $\pi^+\pi^-$ and comparing the $K_L \to 3\pi^0$ in the tagging window with the untagged $K_L \to \pi^+\pi^-$ in the side bands. The corrections and uncertainties are shown in Table 3.

The remaining acceptance correction (about -5×10^{-4}) after K_S lifetime weighting were estimated by monte-carlo simulation. The correction for charged trigger was due to the level-2 trigger efficiency $(91.68 \pm 0.09)\%$ in 1997 data and $(97.75 \pm 0.05)\%$ in 1998.

The statistics for 1998 data sample after background subtraction and mistagging

TABLE 3. Corrections and systematic uncertainties for $\mathrm{Re}(\epsilon'/\epsilon)$ for 1997 data analysis and 1998 preliminary result from NA48. Units on $\mathrm{Re}(\epsilon'/\epsilon)$ are (10^{-4}).

| Source of Uncertainty	1997 data correction	error	1998 preliminary correction	error
Charged trigger	-1.5	±3.8	+0.2	±1.8
Mistagging probability	-3.0	±1.5	-0.2	±1.3
Tagging efficiency	-	±1.0	-	±0.5
Neutral scale	-	±2.0	-	±1.7
Charge vertex	-	±0.8	-0.3	±0.3
Acceptance	-4.8	±2.0	-5.2	±1.5
Neutral background	+1.3	±0.3	+1.2	±0.3
Charged background	-3.8	±0.7	-3.2	±0.5
Beam scattering	+2.0	±0.5	+1.7	±0.5
Accidental activity	+0.3	±2.3	-0.3	±2.0
TOTAL	-9.5	±5.8	-6.2	±4.0
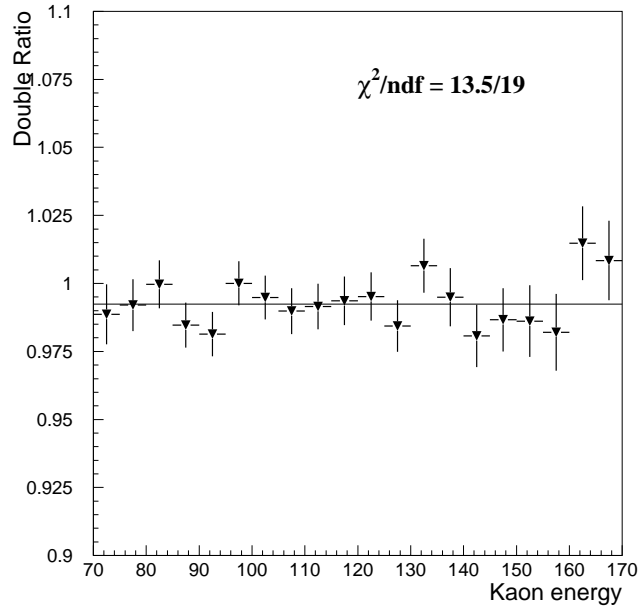
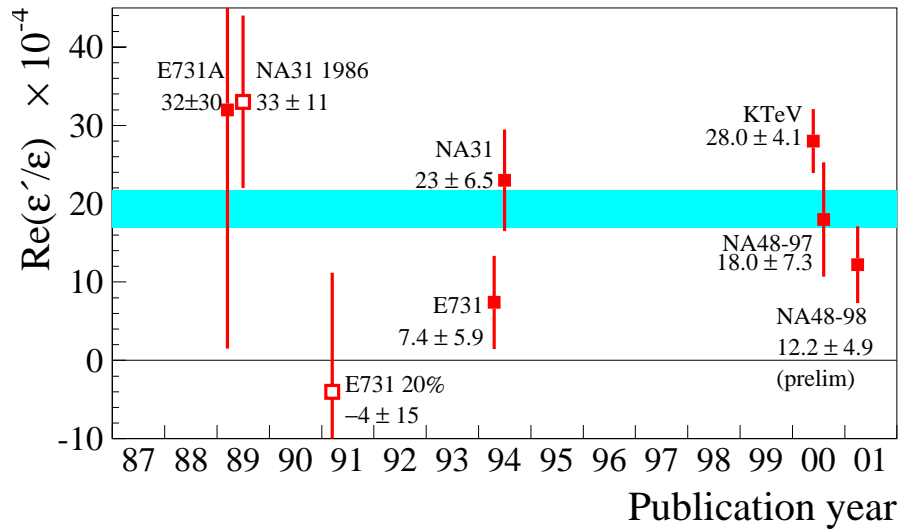**FIGURE 7.** A systematic check of double ratio R vs kaon energy for NA48.

FIGURE 8. Comparison of recent $Re(\epsilon'/\epsilon)$ measurements.

corrections were 4.87M $K_L \to \pi^+\pi^-$ events, 7.46M $K_S \to \pi^+\pi^-$, 1.14M $K_L \to \pi^0\pi^0$ and 1.80M $K_S \to \pi^0\pi^0$. The final result was obtained after applying a series of small corrections as shown in Table 3 with systematic errors. A systematic check of the double ratio R versus kaon energy is shown in Fig. 7. Consistent values were obtained at all kaon energies and there was no significant variation as a function of time and cut variations. Several cross checks has been performed in this analysis.

The result from 1997 data was $Re(\epsilon'/\epsilon) = (18.5 \pm 4.5(stat) \pm 5.8(syst)) \times 10^{-4}$ and from the preliminary 1998 measurement was $Re(\epsilon'/\epsilon) = (12.2 \pm 2.9(stat) \pm 4.0(syst)) \times 10^{-4}$. Combining both together, the new NA48 result was $Re(\epsilon'/\epsilon) = (14.0 \pm 4.3) \times 10^{-4}$, though 3σ above zero it agrees better with the E731 result than KTeV (2.4σ difference). Clearly more precise measurements in the near future are needed from both NA48 and KTeV to clarify this discrepancy.

NA48 will take more data (another 25-30%) in year 2001 at CERN after rebuilding all the damaged drift chambers resulting from an accident at carbon fiber vacuum pipe implosion at the end of 1999. More systematic studies will be done during this run.

SUMMARY

The average of all the measurements from KTeV, NA48, NA31 and E731 is $Re(\epsilon'/\epsilon) = (19.3 \pm 2.4) \times 10^{-4}$ with a not so great $\chi^2/ndf = 11.1/5$. While this result is at the high end of standard-model predictions which supports the notion of a nonzero phase in the CKM matrix, further theoretical and experimental advances are needed before one can say whether or not there are other sources of *CP* violation beyond the standard model. Figure 8 shows the trend of recent experimental results on $Re(\epsilon'/\epsilon)$ since 1986. In next few years we expect $Re(\epsilon'/\epsilon)$ to be

precisely measured by experiments (such as KTeV, NA48 and KLOE) to 5-10% of itself, which would challenge the theorists to further refine their calculations to understand the origin of direct CP violation. This result may well be the most precise measurement in search for "direct" CP-violation in the next 5 to 10 years before upcoming B-physics experiments and the next generation $K_L \to \pi^0 \nu \bar{\nu}$ experiments. The $K_L \to \pi^0 \nu \bar{\nu}$ decay though very challenging experimentally, is essentially pure direct CP violation and can be calculated theoretically very cleanly and precisely [20]. Its branching ratio depends directly on the CP-violating phase of the Standard CKM Model with little theoretical uncertainty. Therefore, an observation of $K_L \to \pi^0 \nu \bar{\nu}$ events in the predicted range would measure directly the magnitude of CP-violating phase in CKM matrix elements. An observation of $K_L \to \pi^0 \nu \bar{\nu}$ outside the range predicted by standard model would indicate interesting new physics [21]. Therefore, by over-constraint the parameters of CKM unitarity triangle through both B and K decays will be the ultimate test to the Standard Model.

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